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STUDY METHOD AND PHYSICS OF HEAT EXCHANGE DURING VAPOR CONDENSATION

N. V. Zozulya

ABSTRACT

The hydrodynamics of heat transfer during vapor condensation are studied, and results are given for quantitative and qualitative aspects of the process. The literature lacks information on design equations for film condensation in condensers with vertical tubes, etc., or film flow. The experimental setup and methods are described in detail. Advantages such as metallic observation mirrors are enumerated.

The wide application of steam condensation processes has made it necessary to study the phenomena of heat transfer which occur in these processes. /32*

The investigations carried out in this direction by Soviet and foreign scientists cover a substantial range of problems. However, in a series of cases for example, during the film condensation of steam in condensers with vertically arranged tubes, the technical literature does not contain accepted design equations for the required surface area of such condensers nor does it contain the established concepts relative to the heat transfer mechanism itself and its association with the hydrodynamics of condensate film flow along the cooling surface. This situation is due to an insufficient amount of experimental data, and their limitation primarily by conditions of water vapor condensation under atmospheric pressure. Also the characteristics of film flow have been studied very little.

The presence of different equations recommended for describing the same process is also due to the disagreement of experimental investigations in the determination of α_1 for the condensation of steam in vertical tubes. The complexity of the phenomenon, the large number of factors which effect heat transfer during steam condensation, is responsible for the wide scattering of experimental data for the case when the purpose of the experiment is to determine

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* Numbers given in the margin indicate the pagination in the original foreign text.

the coefficient of heat transfer during the condensation of water vapor at atmospheric pressure. A comparison of these data (fig. 1) shows that the spread of the measurements is 100 percent and more.

This spread of experimental points is due not only to a possible inaccuracy in the measurements but also to the fact that in some works there was probably a mixed condensation of steam or a condensation of steam with insignificant /33 amounts of air. It is known that in the first case α_1 increases while in the second case it decreases compared to the values of α_1 which must be attained during the film condensation of pure steam.

Experimental investigations were carried out at the Institute of Heat and Power Engineering of the Ukranian Academy of Sciences to refine the existing concepts of heat transfer during film condensation in vertical tubes, to obtain new experimental data on the condensation of steam at atmospheric and subatmospheric pressures, and also to clarify the effect of heat transfer on the physical properties of the film when vapors of highly viscous material are condensed. The present work is concerned both with the qualitative and quantitative aspects of this process.

The present article discusses results of the investigation of film condensate hydrodynamics and describes the special features associated with the experimental setup and the methods which made it possible to obtain reliable data.

Experimental Setup

The experimental setup was designed so that it could be used in the investigation of heat transfer during the condensation of vapors with different physical properties (water and glycerine) and so that it could be used in experiments with tubes of different heights at atmospheric pressure and under industrial vacuum as well as under temperatures from 40 to 200 degrees.

The application of a natural closed circulation of the working agent in the experimental setup (fig. 2) together with its partial automation has simplified the process of obtaining stable modes for any practical duration of experiments.

The figure shows how the saturated vapor of the substance obtained in /35 boiler (1) after flying through the separator and the superheating unit (2) enters the condenser (3). After this the condensate flows through the measuring tanks (5, 6, 7) back into the boiler.

Much attention was given to the problems of maintaining vacuum, hermetically sealing the setup under normal conditions and under conditions of high temperatures and the elimination of air traces. For this purpose the setup was constructed using drawn tubes which were gas welded on both sides. The dismountable couplings were designed in accordance with vacuum engineering practice (ref. 1) and had the form of flange, sleeve, or bellows couplings.

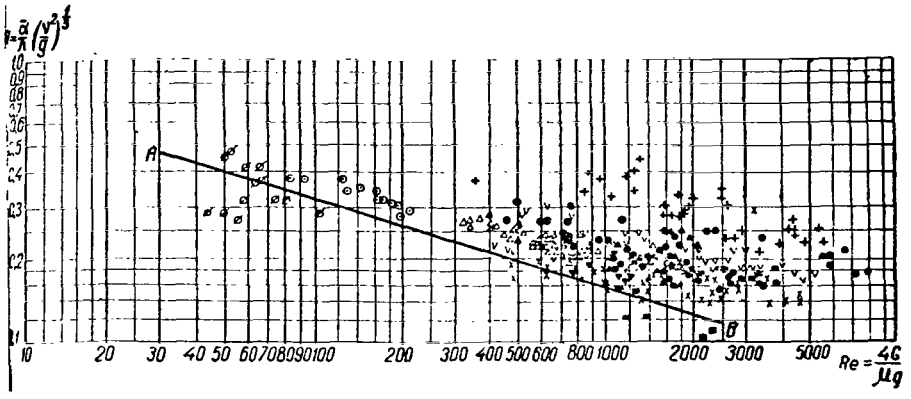

Figure 1. Comparison of experimental data on the condensation of water vapor in vertical tubes:
◊ English and Donkin, □ Callender & Nicholson,
■ Jordan, ⊕ Jacob, Erk, Ek, ● Gebbard and Badger,
▼ Gudymchuk, ▲ Lochkin & Kanayev, v Messenburg,
◊ Kutateladze, + Fredjen, x Becker & Strobe,
⊙ Shee and Kraze, A-B - according to Nusselt.

The shut-off devices consisted of needle valves and vacuum valves. The tiny leaks were eliminated by using BF-2 and BF-4 cements which were polymerized by heating to a temperature of 150 degrees. Tests conducted with an air pressure of 10 atmospheres showed that these measures provided for sufficient hermetic sealing of the setup.

To eliminate traces of air during the experiments a substantial part of the vapor was removed from the basic condenser and fed to an intermediate condenser (4). The condensate was piped to the boiler while the air passed the drop separator, the cooler and the chemical moisture remover and was subsequently pumped by the vacuum-pump (9) into the atmosphere. The vacuum system was regulated by varying the loads on the intermediate condenser and by the control valve. The hermetic sealing of the setup, the large volume (to 20 percent) of vapor moved to the intermediate condenser and a sufficient capacity of the pump have made it possible to carry out the investigations with vapor which was practically pure.

The rather wide range of temperature variations of the experimental tube wall (from 20 to 150°) made it necessary to use an open as well as a closed system for circulating the coolant.

In the first case tap water was used. In the closed system the circulation through a loop consisting of the experimental tube (11) and the heat exchanger (12) was accomplished by pump (13). The heat exchanger was cooled by tap water. The closed system made it possible to use a temperature stable liquid (oil) and to obtain tube wall temperatures above 100°. It also made it possible to maintain a desired difference Δt_{liquid} between the temperature of the coolant entering and leaving the experimental tube. We describe briefly the special features of the different components used in the experimental setup.

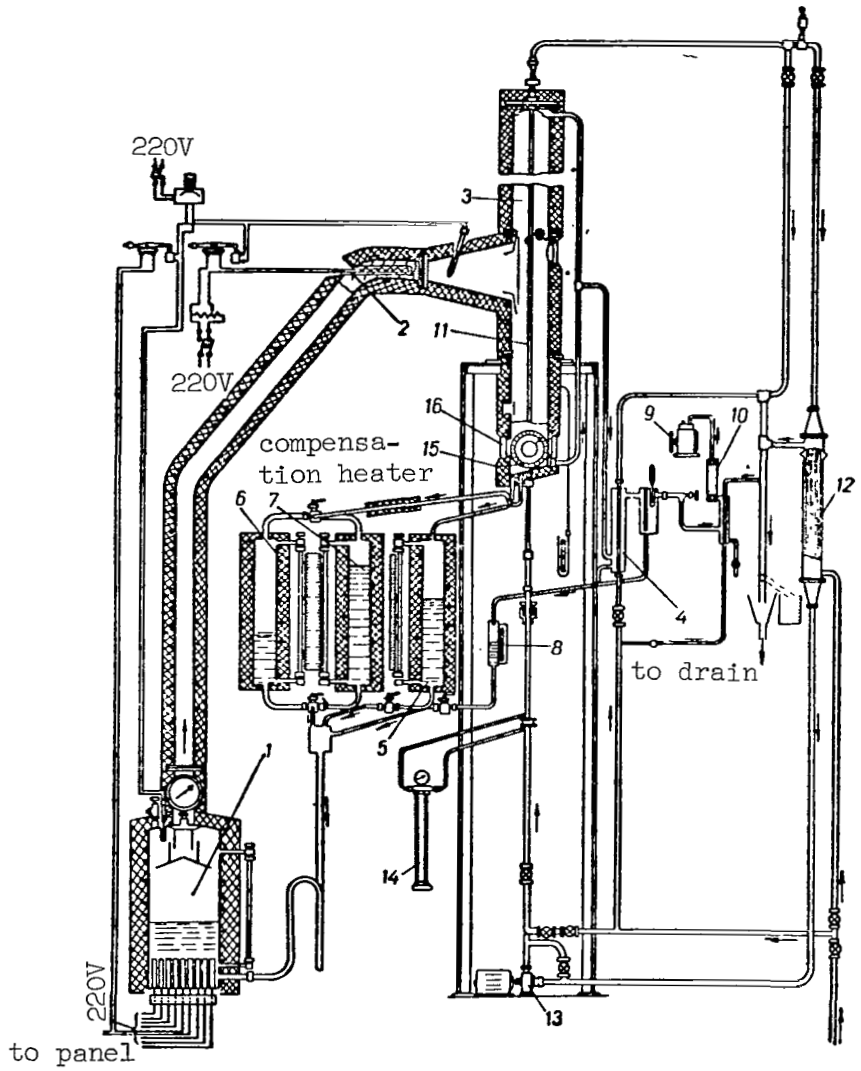

Figure 2. Experimental setup: 1, boiler; 2, steam superheating unit; 3, basic condenser; 4, intermediate condenser; 5, 6, 7, 8, measuring tanks for the condensate; 9, vacuum pump; 10, water remover; 11, experimental tubes; 12, heat exchanger; 13, pump; 14, differential manometer; 15, device for measuring the film; 16, observation windows.

The saturated vapor was obtained by heating the boiler electrically. The heaters were placed in vertical thin-wall steel vessels which were welded into the bottom of the boiler. The insulation of the heaters from direct contact /36 with the liquid prevented the breakdown of glycerine when the latter was used as a working fluid. A sufficient number of heating elements (9 units) and their different power ratings made it possible to vary the load on the boiler from a minimum of 0.7 kilowatts when using one heater to a total of 22 kilowatts when using all the heaters. The operating mode of the boiler was controlled by using

the corresponding number of heater elements. The operating mode during the experiment was maintained automatically by means of a contact thermometer and a mercury relay which operated the central heating element.

For engineering safety, all the heater elements could be simultaneously turned off from a central control point by a magnetic switch.

In spite of the mechanical water separator, the steam obtained in the boiler may contain a certain amount of moisture. To eliminate the moisture content of vapor which is difficult to determine from the thermal balance, an electric superheater was included and placed at the point where the vapor entered the condenser (fig. 2). The superheater was regulated by an autotransformer and a thermal relay. This made it possible to maintain the temperature of the superheated vapor with an accuracy of approximately 1°.

The dismountable construction of the condenser case made it possible to use it with experimental tubes one and two meters in height. The introduction of vapor into the center of the housing with a large diameter (150 mm when the diameter of the experimental tube was 14 mm) make it possible to achieve low vapor velocities (W_{max} = 1.4 m/sec) so that their effect on the flow of film condensate could be neglected.

The end losses of heat through the experimental tube were practically eliminated by using textolite flanges.

Since the basic method of determining the thermal fluxes was the measurement of the condensate formed on the experimental tube, a provision was made for its separate removal from the condensate forming on the walls of the housing.

The housing of the condenser contained a device for measuring the thickness of the film and for visual observations on the nature of its formation and flow and also the leads from pressure and temperature sensors for the vapor in the condenser.

The setup contained regulated compensating heating designed in accordance with the recommendations of B. S. Petukhov (ref. 2).

Measurement Methods

The special feature of the investigation was the comprehensive study of heat transfer and flow hydrodynamics of the condensate film along the tube.

By using working fluids of different properties, of which glycerine has a viscosity which is one hundred times greater than that of water, it was /37 possible to obtain data over a large range of criteria. The range of thermal loads (from 25,000 to 140,000 kcal/m^2 hr) and temperature drops between the vapor and the wall from 6 to 145° covered all the possible operating modes of industrial condensers.

The method of measurement was based on the maintenance of high accuracy in determining the values of the heat transfer coefficient α_1 and in controlling the regulation and stability of the operating mode of the setup when experiments were carried out.

The thermal fluxes were determined from the quantity of condensate and were duplicated for the consumption and heating of the liquid which cooled the experimental tube. In individual cases they were determined from the consumption of the electrical energy in the vaporization of the liquid in the boiler as well as in the superheating of the vapor in the superheating unit.

The condensate was measured by means of measuring tanks which consisted of elongated metallic cylinders. The consumption of the coolant was measured by means of graduated diaphragms while the energy consumed to vaporize and superheat the vapor was measured by a group of electric counters connected to the circuit feeding the heater elements. /38

Temperatures were measured over the entire circulation loop of the working material.

The basic group of measured temperatures consisted of the following: wall temperature of the experimental tube, vapor temperature after the superheater and in the condenser, temperature of the condensate in the measuring tanks, temperature of the liquid cooling the tube, and also the temperature of the condensate flowing down the tube.

Auxiliary measurements included temperature measurement, which made it possible to regulate the direction and magnitude of heat flow during compensating heating.

The measurements circuit (fig. 3) is based primarily on the electric measurement of quantities (resistances and thermo-emf) characterizing the temperature at the points where the sensors were placed.

The measurement of the temperatures associated with the basic group was achieved by using a compensating potentiometric method which provided for high accuracy.

In describing the construction of the sensors we should consider the measurement of cooling surface temperature, the vapor temperature in the volume of the condenser and the film temperature of the condensate flowing down the experimental tube. The first two measurements determine $\overline{\Delta t}$, and consequently their accuracy determines the accuracy of the heat transfer coefficient $\overline{\alpha}_1$.

The measurement of the condensate temperature was achieved at the lower section of the experimental tube. This measurement made it possible to refine the amount of heat necessary to supercool the condensate and gave a more accurate value for the temperature necessary to select the physical constants of the film in determining $\overline{\alpha}_1$.

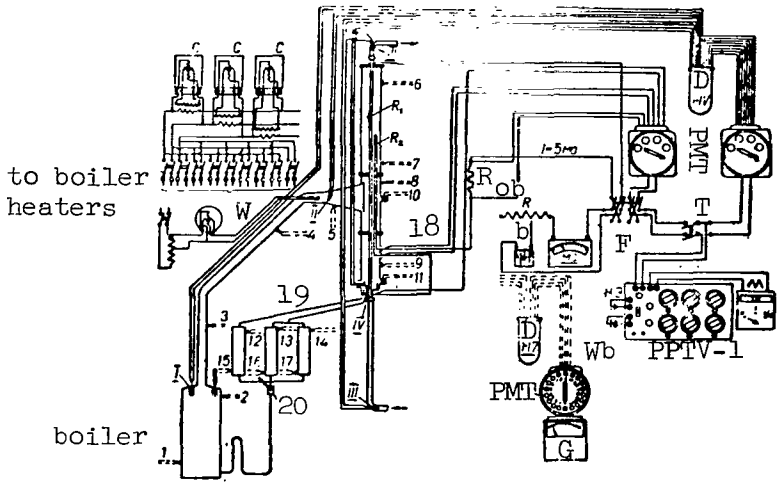

Figure 3. Schematic showing the electrical measurements: C - electric counters (measurement of energy used to vaporize the liquid); W - watt meter (measuring the energy used for superheating the vapor); PPTV-1 - potentiometer; M - "Mul'tifleks" galvanometer; G - galvanometer; T - two pole switch; F - four pole switch; P M T - brush switch; MA - milliammeter; R - resistance; R_{ob} - standard resistance; R_1 - resistance thermometer (temperature of the tube wall); R_2 - resistance thermometer (temperature of the vapor in the condenser); I-IV - thermocouples for measuring the vapor temperature in the boiler, the vapor temperature beyond the superheater, the temperature of the liquid for cooling the condensate; D - Duare vessel; b - battery; 1-17 - thermocouples for measuring the temperature of equipment walls; 18 - condenser; 19 - condensate measuring tanks; 20 - condensate collector.

The measurement of the wall temperature is associated with specific difficulties due to the necessity of placing the temperature sensors in the wall material. The directional method of measurement can lead to substantial errors which are aggravated by the variation in the thickness of the flowing condensate film and the temperature of the coolant and consequently by the wall temperature along the height of the tube.

Two methods are used in the practice of measuring wall temperature: one involves the use of thermocouples while the other involves the use of resistor thermometers (thermistors).

We should point out that in earlier investigations, thermocouples were almost always used. This is explained by the simplicity of their fabrication and installation into the tube wall. However, in order to obtain the average value of the temperature for the entire cooling surface, the basic disadvantage of a thermocouple is that it measures temperature at a point. The use of a large number of thermocouples to obtain the average temperature of the /39

surface makes this determination rather arbitrary and also due to the large number of leads from the tube wall it disrupts the hydrodynamics of film condensate flow along the tube.

Unlike the thermocouple, the resistance thermometer which is installed along the entire length and perimeter of the tube makes it possible to measure the average integral temperature of the tube wall with high accuracy by means of a single measurement without disrupting the nature of the film flow. For this reason the resistance thermometers were used in spite of the difficulty associated with their installation. The resistance thermometers consisted of annealed platinum wire with a diameter of 0.1 mm. Severe difficulties had to be overcome in the fabrication of these devices. The difficulties were associated with the necessity of retaining the quality of the outer surface of the tube and providing a minimum thermal insulation of the platinum while at the same time preventing an electric contact between the platinum and the wall.

After extensive experimentation, the following method of installing the thermometer proved most satisfactory. The platinum wire with the soldered leads covered with thermally stable lacquer over a silk covering was pulled into an annealed copper tube with a diameter of 1.3/0.3 mm. The resistance thermometer in this form was installed in a spiral channel milled in the tube and after it was pressed in, it was soldered along the entire length of the tube.

After the finishing operations, the surface along the solder line was the same as the remaining surface of the tube.

The device was calibrated under conditions which were close to the operating conditions, i.e., after the platinum was installed in the experimental tube. For this purpose the tube with the connected resistance thermometer was placed in a double walled glass jacket through which oil heated to a given temperature was pumped in all directions. The temperature of the oil was maintained with an accuracy of the order of 0.03° by means of an ultrathermostat for each of the established modes.

During the calibration a special experiment was conducted to make sure that the current of 5 ma selected for the thermometer circuit did not have any effect on the accuracy of the measurements. Obviously the variation in the resistance of the platinum due to its heating by the current during the period of measurement lies within the limits of accuracy of the measurements.

The temperature of the vapor in the condenser was also measured with a specially fabricated platinum thermometer in which the platinum insulated with a thin layer of thermally stable lacquer was wound on a long thin tube placed in the condenser. With this type of construction the sensor had low thermal inertia and made it possible to obtain the average value of the vapor temperature in the condenser volume. The vapor temperature was also measured from the pressure sensed by means of a mercury vacuum gage connected to the condenser.

The temperature of the film condensate flowing along the experimental /40 tube was measured at its lower part by placing a thermocouple along the circumference of an irregularly-shaped textolite washer in an arrangement concentric

with the tube. The condensate flowing down the tube covered the hot junction of the thermocouple and its wires, thus preventing the flow of heat from the cold junction. The leads of the thermocouple were moved out of the condenser through special seals. The remaining temperatures were measured either by means of thermocouples or thermometers.

During operation the potentiometric circuit was normalized to correspond to class 2. A "Mul'tifleks" type galvanometer with a sensitivity of $2 \cdot 10^{-9}$a was used as the null device.

To eliminate errors which could be introduced in the resistance thermometer circuits by parasitic thermo-emf, an inversion switching was used which made it possible to change simultaneously the polarity of all the elements in the measurement circuit. Thus the result of the measurements was determined as the average of two readings. All the connections in the measurement circuit were made either by soldering or by arc welding and the circuit itself was mounted on a separate measurement panel.

As part of the measurement technique, in each case before the experiment was started the setup was carefully checked to make sure that it was hermetically sealed. (A test pressure of 3.5 atmospheres was used as well as a vacuum test.) It took 5 to 6 hours to bring the setup from the "cold state" to the operating state which involved regulating the cooling system, the output of the boiler, the superheating of the vapor, the operation of intermediate condensers and the operation of the vacuum pump. The transition from one thermal load to another at a constant vapor pressure took 1 to 2 hours. The experiment lasted 30 to 60 minutes. Measurements were conducted every 5 minutes, while the wall temperature was measured every 1.5-2 minutes.

Due to the automatic regulation of boiler output the pressure in the condenser was maintained at a constant value with deviations of 1-2 mm of mercury from the value established for each experiment. The temperature of superheating was maintained automatically with an accuracy of $1\text{-}2^{\circ}$. Thus experiments were carried out under completely stabilized conditions. As a result of these measures to provide for high measurement accuracy it was possible to determine the value of $\bar{\alpha}_1$ with an error of 5-6 percent.

Qualitative Investigation of the Condensation Process

Many of the works concerned with the investigation of heat transfer during vapor condensation are limited to the determination of the heat transfer coefficient without a direct study of the nature of formation and flow of condensate film along the cooling surface. As we know the visual observations were first established by V. A. Gudymchuk (ref. 4) and S. S. Kutateladze (ref. 5). However, the applied method of observation on the state of the cooling surface /41 through the observation windows turned out to be inadequate. Such observations (if the glass wall does not extend along the entire tube) are limited to definite regions. Also the method itself cannot give a clear picture on the nature of the condensate film flow along the tube.

This situation made it necessary to find another method of observation. After a series of attempts it turned out that the form of vapor condensation and the nature of the condensate film flow can be clearly observed from the mirror reflection of the condensation surface. To obtain this reflection mirrors were placed inside the condenser housing.

The uniform illumination of the tube walls facing the mirror was achieved by arranging light sources in the condenser. The intensity of these sources was regulated by varying the voltage which fed their circuit.

To make high-temperature operation possible, metallic mirrors were used. To eliminate the condensation of vapor on the surface of the mirror compensation was provided by heating the back side of the mirror.

The mirrors were arranged against the observation windows and were mounted into the condenser housing. By installing the mirrors at a certain angle with respect to the experimental tube it was possible to observe the regions of the tube to any desired height.

This new method has made it possible to observe and determine a series of important features associated with the process.

The qualitative studies showed that when water vapor at a pressure close to atmospheric is condensed on the copper tubes mixed condensation occurs. However, the intensification of the heat transfer at this time is determined not only by the presence of regions with droplets but also by the disruption in the laminar flow of the condensate film which flows over and periodically covers these regions.

The increase in the viscosity of the condensate (by condensing the vapors of a viscose substance or by dropping the pressure of the water vapor condensation) limits the occurrence of droplet condensation. In this case the increase in the thickness of the condensate film and in the binding forces between the particles of liquid inhibits the exposure of the cooling surface at points of possible droplet formation. Consequently, under conditions of industrial vacuum the calculation of $\bar{\alpha}_1$ must be based on the laws governing the film condensation of vapor.

Two forms of condensate film flow were clearly established during the film condensation of water vapor. At the upper part of the tube the film undergoes laminar flow in a uniform fashion without any visible disruptions in the outlines of its external free surface. Then after it has reached a definite thickness, the film develops a surge which generates clearly defined ring waves. The height of these waves increases as they move down and the entire picture resembles a corrugation with rolled ribs and a poorly defined conicity (fig. 4).

When glycerine vapors are condensed the viscosity is much greater than the viscosity of water and the smooth laminar flow of the film is transformed /42 into a flow of built up layers having the appearance of individual elongated waves.

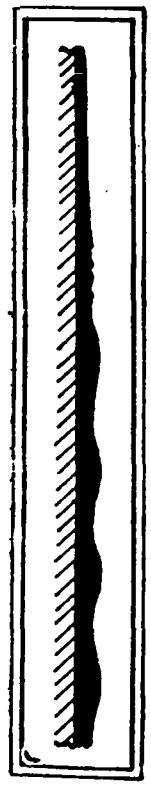

Figure 4. Nature of film flow along the vertical tube of the condenser.

The length of the laminar region is variable and depends on the magnitude of the thermal flux if all other conditions are equal, tending to become shorter when the latter increases.

The complex nature of the operation when qualitative investigations to measure the film thickness are conducted in parallel with the investigations to measure $\bar{\alpha}_1$, made it possible to establish the limits for the transition of the laminar flow to wave flow. This transition during the condensation of water vapor occurs when

$$Re_n = \frac{4qH}{r\gamma\nu} = 25\text{-}35,$$

where q is the specific thermal load; H is the height of the tube; r, γ, ν are physical constants. This is in agreement with the derivation of P. L. Kapitsa (ref. 6) for the beginning of wave formation in thin liquid films.

In the determination of $\bar{\alpha}_1$ it was observed that the process of heat transfer through the film is intensified as wave flow is developed on the cooling surface.

This led to the conclusion that under conditions of vapor condensation in vertical tubes there is a transition zone between the laminar and turbulent flow states which is associated with the wave flow of the film.

The processing of experimental data to obtain the coefficients of heat transfer in the form of criteria showed that the extent of this zone lies in the limits $30 < Re_n < 2{,}000\text{-}2{,}500$ and in this case $\bar{\alpha}_1$ can be determined from the relationship $\frac{\bar{\alpha}_1}{\lambda}\left(\frac{\nu^2}{g}\right)^{\frac{1}{3}} = 1.05\,Re^{-\frac{2}{9}}$.

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